NON-INTRUSIVE DETECTION OF SOIL PROPERTIES FOR PRESSURE-DRIVEN PROCESSES

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ABSTRACT

The state of the ground can change dramatically in response to changing meteorological influences and physical disturbances of the ground (e.g. tilling) that are important to many civilian and military activities. Permeability is the fundamental parameter of a porous media that controls whether a surface is an acoustically hard one, through which fluids may not easily penetrate, or conversely a more transparent surface, across which gas and water may readily move. Permeability is the property that controls pressure-driven processes including rain infiltration in soils, surface-atmosphere gas exchange, and acoustic response of the ground. Traditionally it has been assumed that atmospheric acoustic waves do not significantly penetrate the ground. In this paper we describe a new result showing that for some common ground surface materials, acoustic wave propagation in the atmosphere can induce pressure propagation into the ground to sufficient depths to permit the non-intrusive detection of soil permeability across the ground surface.

1. INTRODUCTION

Laboratory measurement techniques for determining permeability of porous media exist for centimeter-scale samples (e.g. Albert et al, 200), and field “slug tests” are commonly used for groundwater hydrology and deep infiltration (e.g. Bouwer, 1978). Yet for many hydrological and military applications, knowledge of permeability is needed on lateral scales up to tens of meters, and on vertical scales of less than a meter. In porous media, permeability is the material parameter that controls pressure-driven processes, for example the passage of an acoustic (pressure) wave through the medium, the flow of gases between the soil and the atmosphere, and the infiltration of rain water or other liquid into the soil. Previous measurements relating to fluid flow through soil have typically been done as "point"-type measurements with permeameters that measure fluid flow and pressure drop across a sample of the material; multiple ways of doing this are described in Dullien (1979). In the acoustics research community, previous outdoor acoustic measurements have determined empirical factors that relate to the effective flow resistivity and relative permeability (e.g. Cramond and Don, 1985; Attenborough,1992; Albert, 2001, Sabatier et al, 1990, Moore et al 1992). However, because these factors contain dimensionless, model-dependent scaling factors, the absolute permeability on scales of one to tens of meters over shallow depths is still unknown. Research into non-intrusive detection of surface permeability was not contemplated because, prior to this research, it had often been assumed that pressures due to surface acoustic sources do not penetrate into the ground surface. In the next section we will briefly review the literature on various aspect of near-surface permeability, then we present a theoretical study designed to determine whether using acoustics to determine ground surface permeability is feasible by assessing the depth of penetration of a pressure wave induced by an atmospheric point acoustic source.

2. BACKGROUND

There are a variety of techniques for measuring permeability of cm-scale samples (e.g. Dullien, 1979; Albert et al, 2000). Sample-scale air permeability measurements can be made in the field and can be quantitatively related to saturated hydraulic conductivity (Loll, 1999) to within natural variability in soil hydraulic conductivity field measurements. However, it is labor intensive and it is often difficult to get an undisturbed sample; this is important because the nature of the interconnected pore space controls the permeability. Air permeability measurements on samples from structured soil with samples of different sizes (100 cm^3 and 3140 cm^3) show that small samples generally yielded lower values and a higher variability in permeability than larger samples (Iversen et al, 2001). This implies that correlation in permeability measurements across a range of scales will depend on the degree of soil structure or layering in the sample. Mallants et al (1996) found that macropores and small sampling volume both contribute

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to spatial variability in permeability measurements at the cm scale. Air permeability measurements of cm-scale samples in an undisturbed constructed field of sandy loam in Japan showed spatial correlation, and measurements on larger samples (3140 cm^3) were similar, indicating this site had little small-scale heterogeneity; however, measurements taken 4 months later show that tilling and precipitation caused a significant increase in permeability (Poulsen et al, 2001). Heterogeneity in soil moisture at a flat silt loam site was spatially dependent over a distance of 0.5m, but maximum variances increased linearly with decreased mean soil moisture as the soil dried (Melloh et al, 2005), hinting that correlation lengths may reflect soil properties but variances indicate moisture level. Higher near-surface permeability permits a spatially variable response to microtopographically focused infiltration of surface water (Keller et al, 1988). In natural conditions, spatial heterogeneity or lack thereof varies from site to site, for example, field measurements including salinity in Iran (Hajrsuliha et al, 1980) show some site-dependent conditions requiring geostatistical analysis, while nearby others are spatially independent. In studies involving many different soil properties and chemistry, Kravchenko et al (1999) found that multifractal parameters reflected many of the major aspects of soil data variability and provided a unique quantitative characterization of the data spatial distributions.

Thin section (petrographic) analysis of geological materials is a traditional, well-known tool to examine the relation between porosity and permeability on a microscopic scale. This analysis allows for the measurement of bulk mineral composition, grain fabric and texture as well as a classification of porosity and permeability types. With a polarizing petrographic microscope, examination of a two-dimensional cross-section thru microstructural features is possible, and the relationship between the microstructures, permeability, and porosity on the grain scale can be examined and evaluated (e.g. Harrelson et al 2001; Harrelson et al, 1996). Additionally, the scanning electron microscope (SEM) can be utilized to examine microstructures at a significantly higher magnifications and resolution. The SEM can look directly into porous zones associated with microstructures and determine mineral distribution and pore-throat geometry of porous media.

Considerable attention has been paid to near-surface acoustic-to-seismic coupling for land mine detection (e.g. Xiang and Sabatier, 2002; Valeau et al, 2004; Korman and Sabatier, 2004; Fokin et al, 2006). Those studies investigated the mechanical response of the soil particles to an acoustically-induced seismic wave; the results are relevant to compressional waves in the soil matrix, which is made up of the soil particles. We note that those studies are important but address a different physical phenomenon than the topic of this, our current paper, which is to investigate the compression of air within the pore space of the soil due to a surface acoustic pressure wave. The soil permeability is a measure of the nature of the interconnected pore space in soil, and reflects movement of the fluid within the pore space and not the compression of the soil matrix.

Many acoustic measurements have been conducted to characterize ground surfaces, but all have stopped short of linking the results with the fundamental soil property of permeability. Empirical factors have been determined for acoustics over porous media (e.g. Albert, 2001; Attenborough, 1992; Don and Cramond, 1985) however these factors, called effective flow resistivities, depend on the particular acoustical model employed and have not been linked to the fundamental material parameter, permeability. In addition, many acoustic models also include dimensionless “shape factors” that are used to adjust the models to agree with measurements. Previous acoustic measurements to determine soil properties determined the relative, not the absolute, flow resistivity or permeability of the soil (Sabatier et al 1990, Moore and Attenborough 1992). Attenborough’s “four parameter” model of ground impedance (1985) is widely used in studies of outdoor sound propagation and is more accurate than the simpler empirical model of Delaney and Bazley (1970), especially at lower frequencies. However Sabatier et al. (1993) have shown that the four parameters are not independent, and Allard has shown how the parameters of this model are related to the DC flow resistivity of the porous material. Variations in the relative permeability are greater by an order of magnitude from model differences.

Typical values of permeability span many orders of magnitude for natural soils, depending on the type of soil. Table 1 shows that coarse gravel, with a typical permeability of 1 x 10^{-7} m^2, is more than seven orders of magnitude more permeable than silt, which has a typical permeability of 5 x 10^{-15} m^2.

Material	Permeability (m^2)
gravel	1.0 x 10^{-7}
fractured rock	1.0 x 10^{-7}
seasonal snow	3 x 10^{-9}
sand/gravel mix	1 x 10^{-9}
loamy sand	5 x 10^{-12}
fine sand	1 x 10^{-12}
fine clay	6.0 x 10^{-14}
silt	5 x 10^{-15}

Table 1. Typical permeability values for a range of surface materials.

While it is recognized that the nature of the ground surface impacts atmospheric acoustic wave attenuation, it has often been assumed that pressures due to surface acoustic sources do not induce significant compression of the air in the pore space in the near-surface soil. If acoustic waves can penetrate into depths of the soil surface at depths that are relevant to trafficability, tilling, and surface-atmosphere gas exchange, then acoustics might be used in a way that it has not been used before, to non-intrusively determine the permeability in the near-surface soil. The purpose of this paper is to provide the scientific basis for the theoretical depth of penetration of the acoustic pressure wave, which is a critical step in the path of our ongoing and future studies in non-intrustive detection of near-surface properties.

3. METHODS

We lay the scientific foundation by conducting a theoretical study to determine the feasibility of using acoustics for permeability determination by discovering the depth of penetration of a point source acoustic wave into the pore space of the soil. We will employ the the inversion techniques with waveform analysis of the acoustic signature at the various locations to determine the depths to which surface acoustical pressure will penetrate in a variety of surface soils. Albert (2001) established a time domain waveform inversion procedure designed for determining material properties of snow by matching the waveform from field experiments to theoretical waveforms produced by forward modeling of acoustic wave propagation for a point source. The results of that study showed that for homogenous snow, the effective flow resistivity and the depth of the snow pack were the controlling features of the resulting waveform, and pore shape factors were of secondary importance. We employ the model (Albert, 2001) to determine the depth of penetration of a point source acoustic wave into soils of various types.

The forward model calculates theoretical acoustic pulse waveforms given the surface properties, using the method described by Albert (2001). The acoustic pressure P measured at a receiver on the surface a slant distance r away from a monofrequency source in the air is given by

$$\frac{P}{P_o} = \frac{e^{ikr}}{kr}\left(1+Q\right)e^{-i\omega t}$$

where P_o is a reference source level, k is the wave number in air, and Q is the spherical wave reflection factor representing the effect of the ground. At high frequencies, Q can be written as

$$Q = R_p + (1-R_p)F(w)$$

where R_p is the plane wave reflection coefficient, F is the boundary loss factor, and w is the numerical distance, all of which depend on the specific surface impedance Z of the ground. The impedance and Q are both dependent upon frequency. Indicating a particular frequency n by F_n, once Q_n is determined the response P_n can be written as

$$P_n = \frac{P_o}{4\pi r} S_n W_n (1+Q_n) e^{\rightarrow i2\pi f_n r/c}$$

for n=0,1,2,…,N-1 and where Sn and Wm represent the source and instrument effects, respectively, and c is the speed of sound in air. An inverse FFT is used to construct theoretical pulse waveforms in the time domain:

$$P_m = \frac{1}{N}\sum_{n=0}^{N-1} P_n e^{-i2\pi mn/N}$$

For a two-layered model of the ground where d is the upper layer thickness, k_2 is the wave number in the layer, and Z_2 and Z_3 are the impedances of the two layers:

$$Z = Z_2 \frac{Z_3 - iZ_2 \tan k_2 d}{Z_2 - iZ_3 \tan k_2 d}$$

The acoustic behavior in the soil is specified by the specific impedance Z_2 and the wave number k_2, which are used in the equations above to find the waveform.
The parameters were calculated using the four-parameter model of Attenborough (_) for ground impedance. The four input parameters are the effective flow resistivity σ, the porosity Ω, the pore shape factor ratio s_f, and the grain shape factor n'. The layer depth d and the substrate properties are also needed in a layered model. The propagation constant k2 and the characteristic impedance Zc are given by

$$k_2 = \frac{\omega}{c_o} q \frac{C^{1/2}}{B^{1/2}}$$

$$\frac{Z_c}{\rho_o c_o} = \frac{q}{\Omega}\frac{1}{B^{1/2}C^{1/2}}$$

where

$$B = \left[1 - \frac{2}{D}T\left(D\right)\right]$$

$$C = \left[1 - \frac{2(\gamma-1)}{N_{\mathrm{Pr}}^{1/2} D}\right]$$

$$T(x) = \left[J_1(x)\right]/\left[J_o(x)\right]$$

J_1 and J_o are cylindrical Bessel functions,

$$D = \lambda\sqrt{i}$$

$$\lambda = \frac{1}{s_f}\left[(8\rho_o q^2\omega)/(\Omega\sigma)\right]^{1/2}$$

$$q^2 = \Omega^{-n'} = tortuosity$$

And γ is the ratio of specific heats (1.4 for air), N_{pr} is the Prandtl number (0.71 for air), and $\omega=2\pi f$. For the calculations herein, the shape factor n' was set to 0.5 for spherical grains, and the porosity was determined from the density.

Our theoretical determination of the depth of penetration of an acoustic pressure wave into a homogenous porous medium is based on the premise that, in the absence of an impermeable lower boundary that could shield the underlying media from the pressure wave, the extent of media below the true penetration depth in a homogeneous media does not significantly affect the waveform. We use this idea together with forward modeling of waveforms over a variety of porous media and the time domain waveform inversion procedure to determine the depth of penetration.

The simulation for each material type proceeds as follows. The forward model is run to simulate an acoustic pulse laterally propagated above a deep uniform porous material 10 m in depth with prescribed permeability and porosity, underlain by a material which is less permeable by a factor of 100. For a surface acoustic pulse, the 10 m depth essentially represents infinite depth. A sample resulting waveform is shown in the top panel in Figure 1. The top panel shows the source pulse (on the left), and the resulting waveform showing the pulse as received by a receiver on the ground surface 60 m distant, situated over a deep layer of uniform soil. The same source pulse is used in all of the subsequent simulations, although it is now shown on the subsequent panels.

Next, a series of forward model runs were made to simulate propagation over the same soil type, but of different depths. The different depths were indicated in the model by situating the impermeable lower boundary to the various prescribed depths. The panels in Figure 1 below the top panel show the resulting waveforms for soil depths of 20, 35, 50, and 65 cm. In each panel, the original waveform over deep soil is shown as a dotted line, while the waveform for each depth is shown as a solid line.

It is evident that the shallow depths show less dampening of the waveform, and the waveform is very different than that in the top panel for the deep soil. As the depth of the soil is increased, the waveforms come into better agreement with the deep waveform. At some depth which is significantly shallower than the bottom boundary, the waveform matches that for the deep soil to within a certain criterion. We selected the L1 norm as a goodness of fit criteria to determine the shallowest waveform that shows good agreement with the deep waveform. This norm is the sum of the absolute values of the differences between the deep and a shallow waveform over a fixed time window. The inverse waveform matching technique (Albert, 2001) was used to automatically select the waveforms that minimize the L1 norm for waveforms calculated from the forward model. This provided an unbiased means of determining the shallowest depth whose waveform was a good match with that from the deep soil. The depth determined by the waveform matching is the effective depth of penetration of the surface acoustic pressure. For the example shown here, the acoustic wave penetrates to 65 cm depth into a porous medium of porosity 0.781 and permeability of 1×10^{-10} m^2. This process was repeated for a wide variety of soil types.

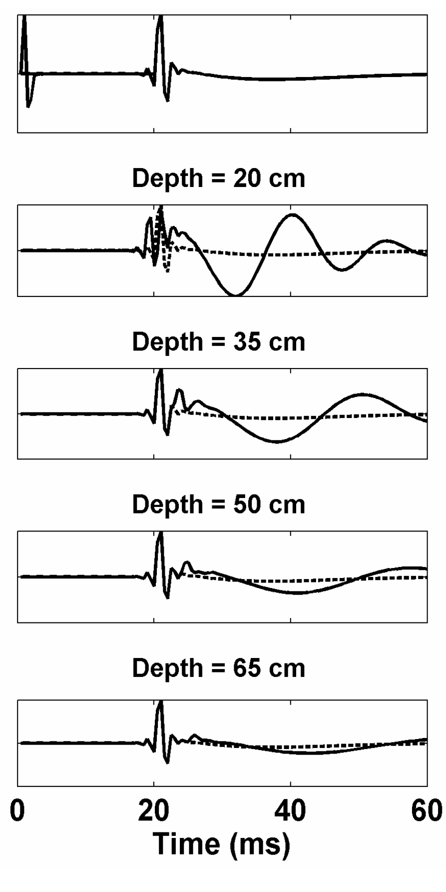

Figure 1. *Top panel*: Waveform from the forward model assuming deep, uniform porous media with porosity of 0.78 and permeability 1×10^{-10} m^2. *Subsequent panels:* Comparisons of forward modeling waveforms for various porous media depths (solid lines) compared with the waveform for deep media (dotted line).

4. RESULTS

We used this procedure to investigate a number of soils representing a range of material properties, from highly permeable gravel and snow to less permeable silt. The resulting depths of penetration is shown in Figure 2. It is evident that the ability for an acoustic pressure wave to penetrate a soil is dependent upon the permeability of the soil. The most permeable soils are those for which the acoustic wave has the deepest penetration. Low permeability materials like clay will have a penetration depth less than a centimeter. In contrast, dry gravel, snow, and sand & gravel mixtures show penetration depths greater than ten centimeters, and greater depths in coarse gravel. These are significant depths for many military and civilian applications, for example tilling impacts on soil properties, infiltration of rainfall for trafficability, and surface-atmosphere gas transfer.

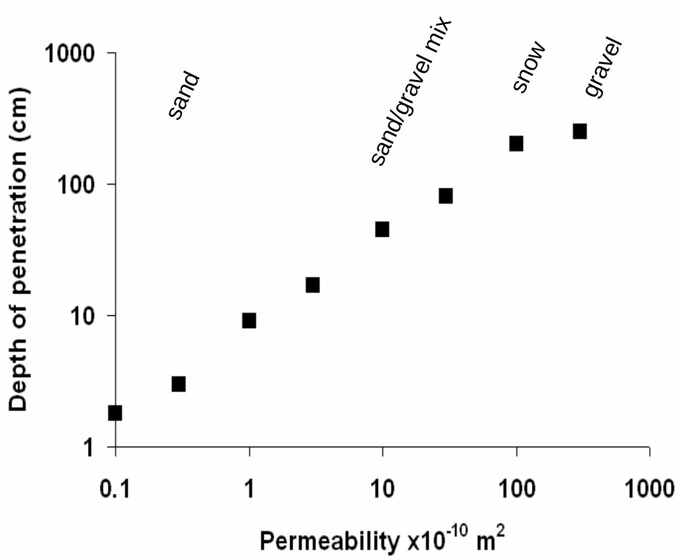

Figure 2. Depth of penetration of a surface acoustic pressure wave as a function of permeability representing a range of soil types.

CONCLUSIONS

In contrast to traditional assumptions that atmospheric acoustic signals do not penetrate the ground, we have shown that surface acoustic signals can penetrate to depths from centimeters to tens of centimeters in commonly occurring porous materials such as sand, snow and gravel. The depth of penetration of the acoustic wave is proportional to the permeability of the porous media, across a wide range of values. This discovery provides the scientific foundation for our further investigation of the use of acoustics to non-intrusively determine the permeability of the near-surface soil.

In continuing research, we will build upon this finding to non-intrusively measure the permeability of a variety of surface materials, including effects of soil moisture and spatial variability in soil properties. Non-intrusive measurement of permeability in the near-surface soil can provide a leap-ahead that provides the means for investigating a range of problems, including the state of the ground in response to changing meteorological influences and spatial variability in soil properties, which are important to many civilian and military applications.

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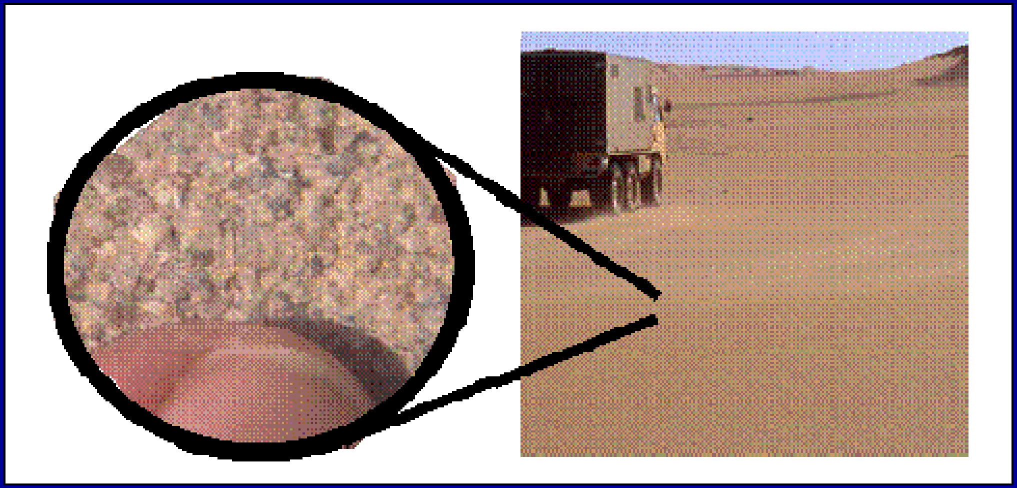

US Army Engineer Research and Development Center

Outline

- The Problem
- Background
- Theory
  - Approach
  - Results
- Data
  - Field measurement
  - Results
- Conclusion

The Problem

- The properties of the ground surface can change dramatically in time due to human activity or weather.

- Pressure-driven processes in porous media are controlled by the intrinsic permeability, a fundamental property of the porous media.

- Non-intrusive assessment of permeability would facilitate assessment of conditions for a wide variety of applications.

- There is no method for non-intrusively measuring surface permeability on scales of meters.

A Stumbling Block

- Traditionally it has been assumed that surface acoustic pressure waves do not penetrate more than several millimeters into the soil.

- Our results challenge that assumption and provide the basis for a new approach.

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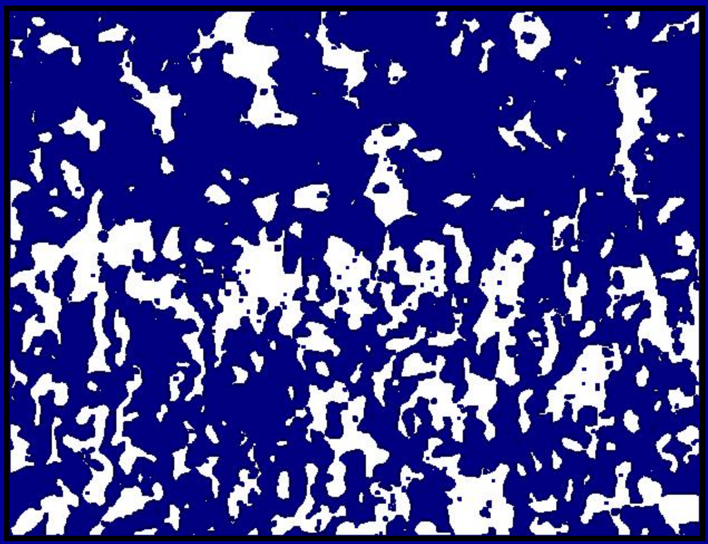
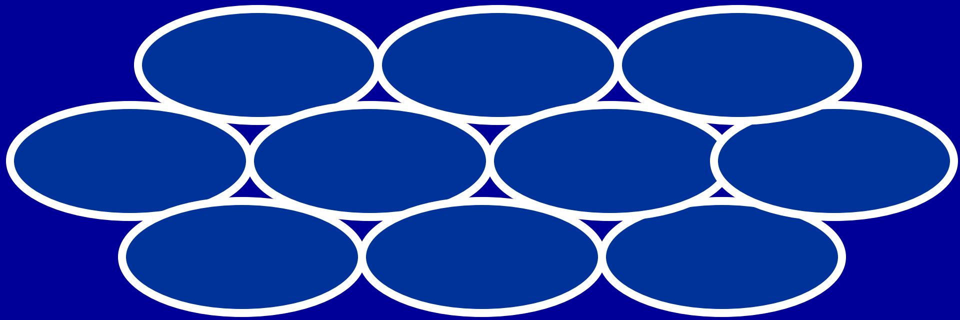
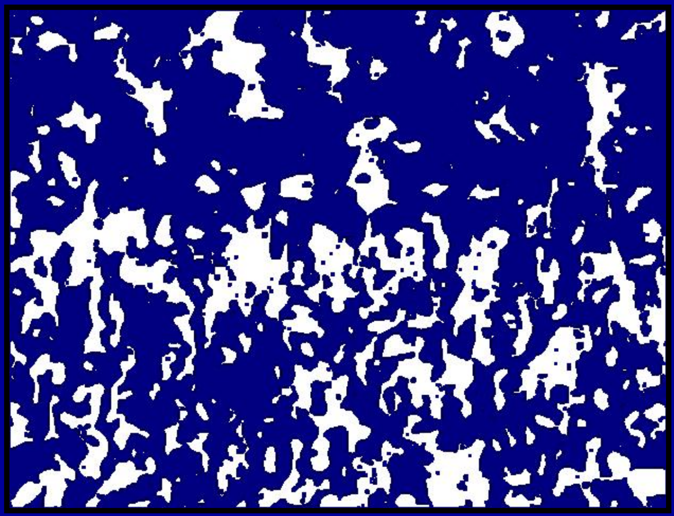
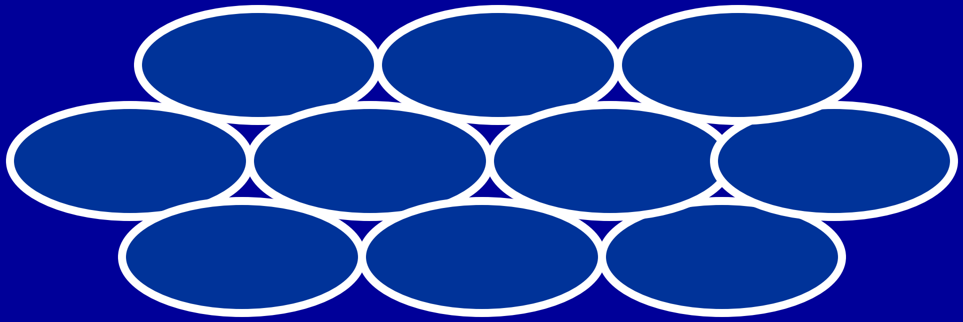
What is Permeability?





What is Permeability?





Permeability is a material property of porous media that reflects the nature of the interconnected pore space.

Permeability controls pressure-driven processes including rain infiltration in soils, surface-atmosphere gas exchange, and acoustic response of the ground.

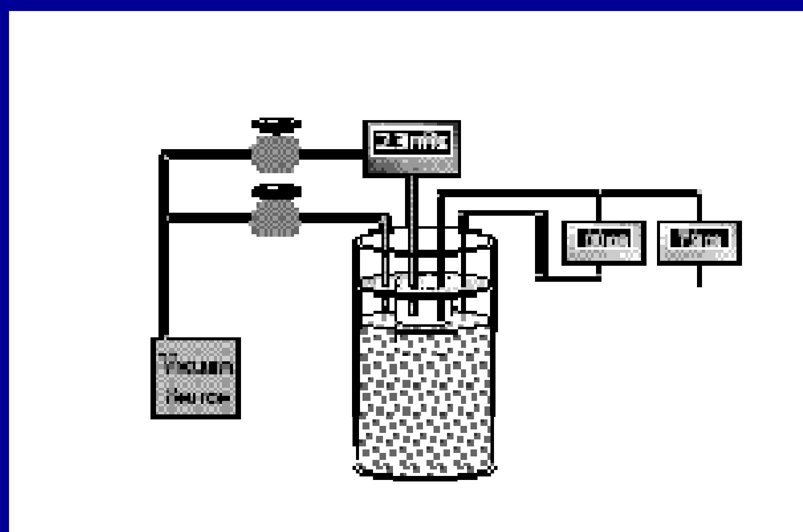
Natural porous media spans a wide range of permeability

Material	Permeability (m^2)
gravel	1.0×10^{-7}
fractured rock	1.0×10^{-7}
seasonal snow	3×10^{-9}
sand/gravel mix	1×10^{-9}
loamy sand	5×10^{-12}
fine sand	1×10^{-12}
fine clay	6.0×10^{-14}
silt	5×10^{-15}

These variations result in large differences in water infiltration and exchange of gases, heat, and mass across the ground-atmosphere interface.

Traditional permeability measurement

- Lab techniques exist for measuring permeability of a soil sample on a scale of centimeters.
- Slug tests are used in groundwater hydrology for sampling field-scale permeability.



Traditional surface acoustics

- ‘Effective flow resistivities’ determined for acoustics over porous media (e.g. Albert, 2001; Attenborough, 1992, Don & Cramond 1985) are model-dependent and not fundamental material properties.
- Relative flow resistivity & ground impedance determined by acoustics have not yielded permeability determinations (e.g. Sabatier et al 1990, Moore & Attenborough 1992).
- Considerable effort on acoustic-to-seismic coupling (e.g. Xiang and Sabatier 2002, Fokin et al 2006) relate to mechanical response of the soil matrix, not compressional air wave within the pore space.

Outline

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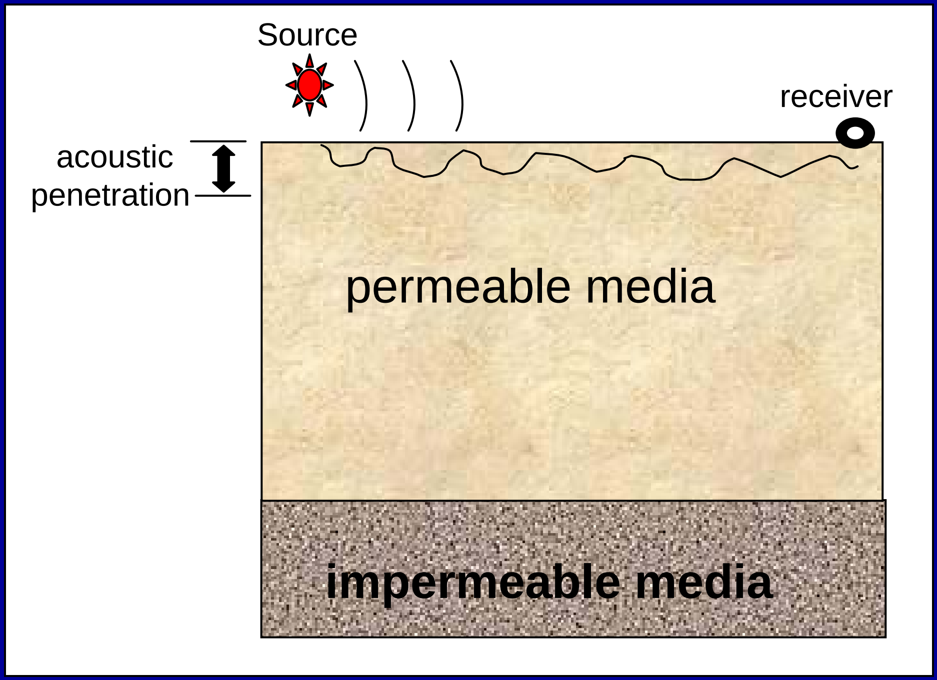
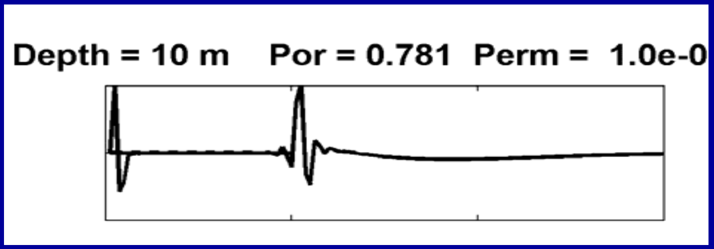
How deep does a surface acoustic wave over ground penetrate the ground?

Biot theory - calculate acoustic pulse propagation above a porous ground



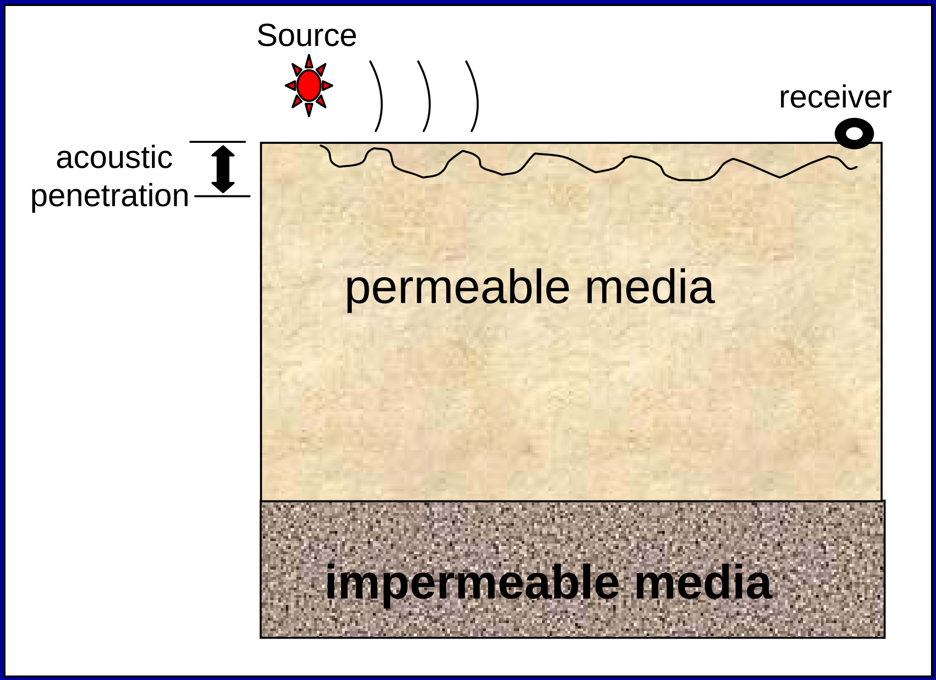


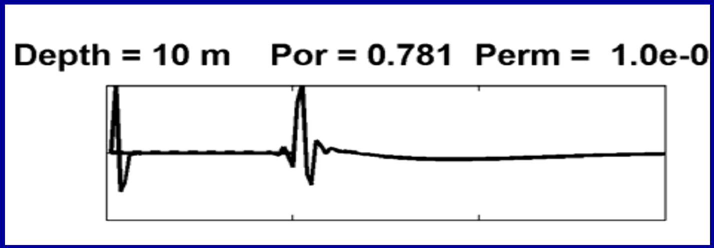
Surface acoustic waveform

Because the ground is porous, the acoustic pulse interacts with the compressible interstitial soil air and becomes distorted.

Acoustic penetration depth

1. Calculate the surface acoustic waveform for a given soil type, assuming very deep (10 m) uniform permeable media of specified permeability.

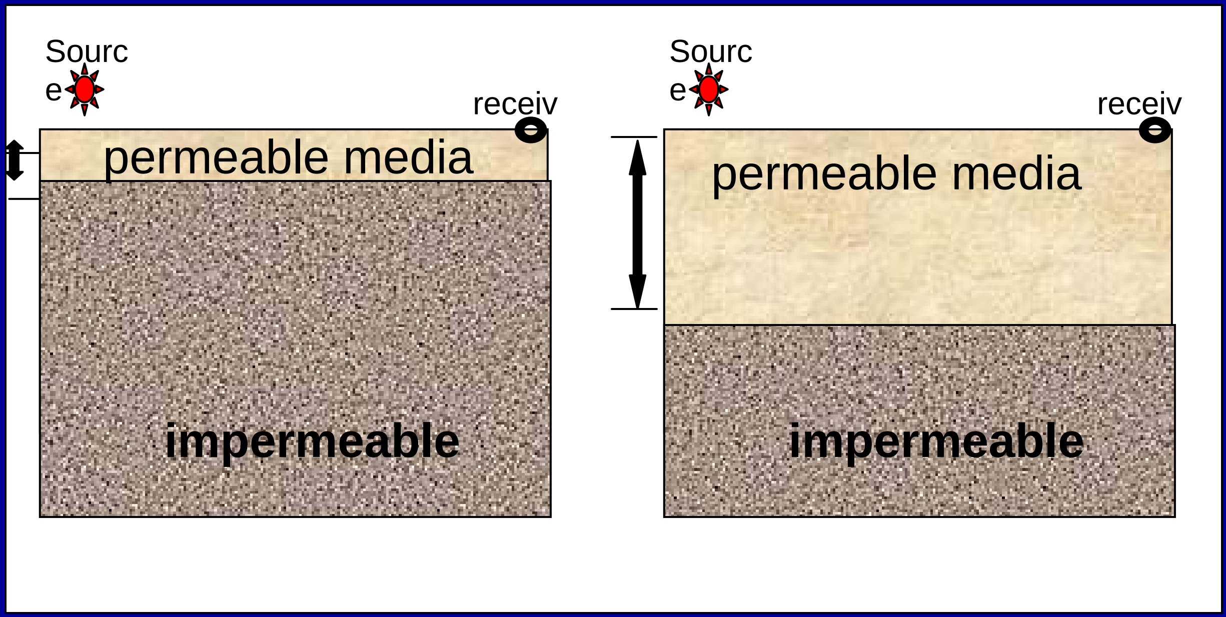


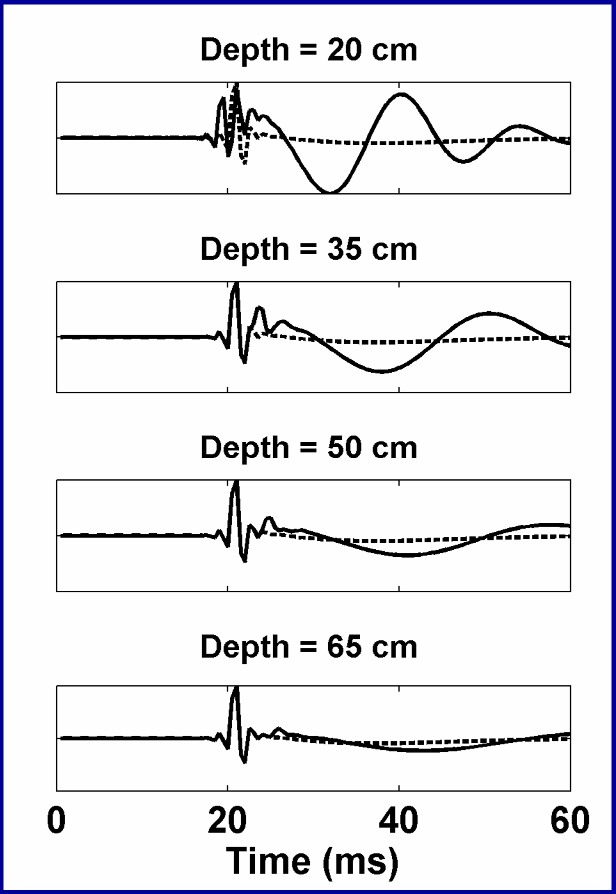


Surface acoustic waveform

Acoustic penetration depth, cont'd

2. Repeat the calculation with the soil thickness layer changing, to determine the change in the pulse shape.



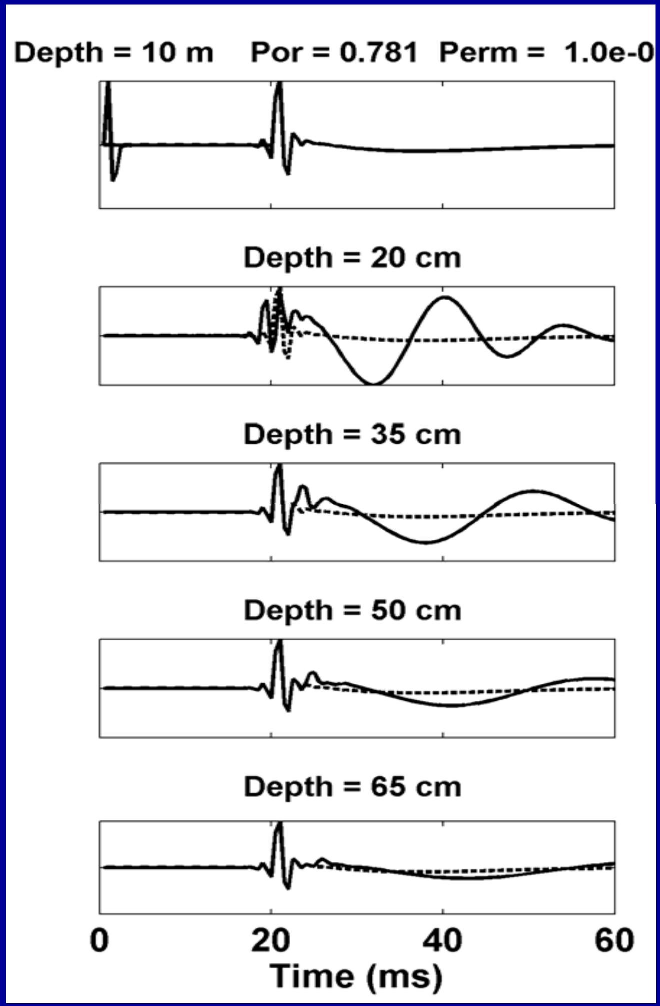


Waveforms change as soil layer changes

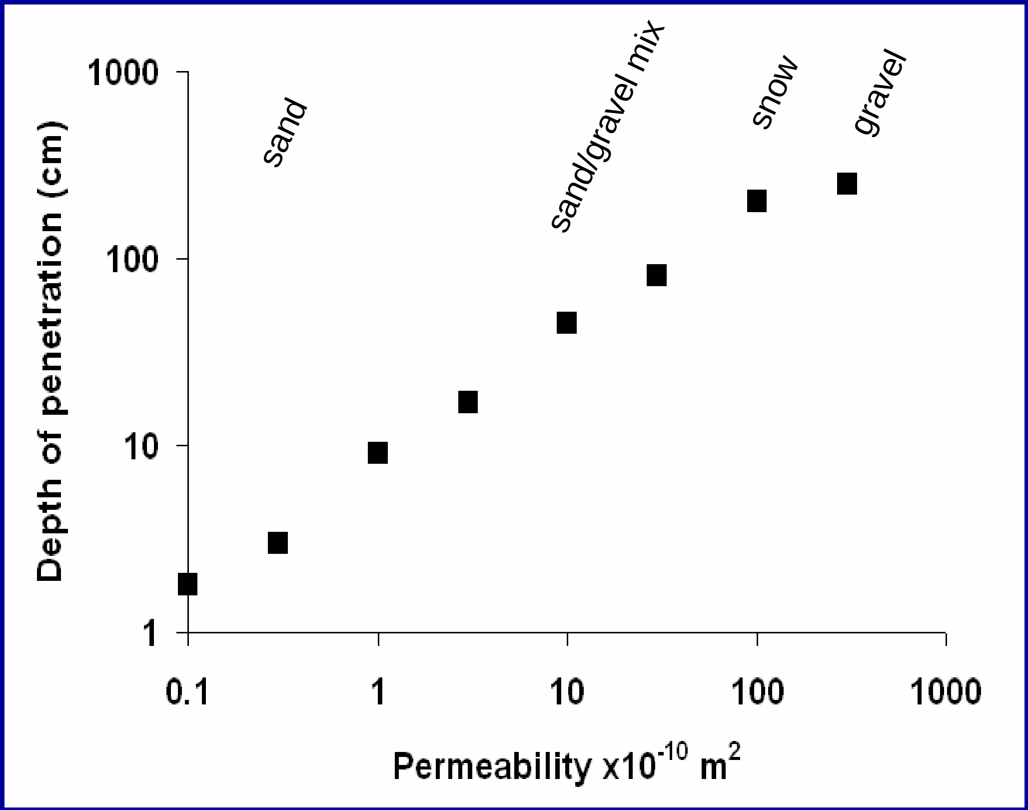
Surface waveform shown as dashed line.

Acoustic penetration depth, cont'd

3. Match waveforms to determine the depth of penetration of the acoustic signal for that soil.



Theoretical Results

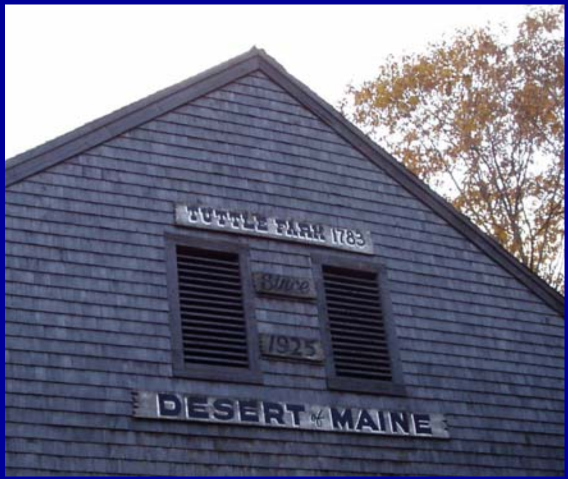


Depth of penetration ranges from 1 to 100 cm depending on the type and mix of sand / gravel.

Outline

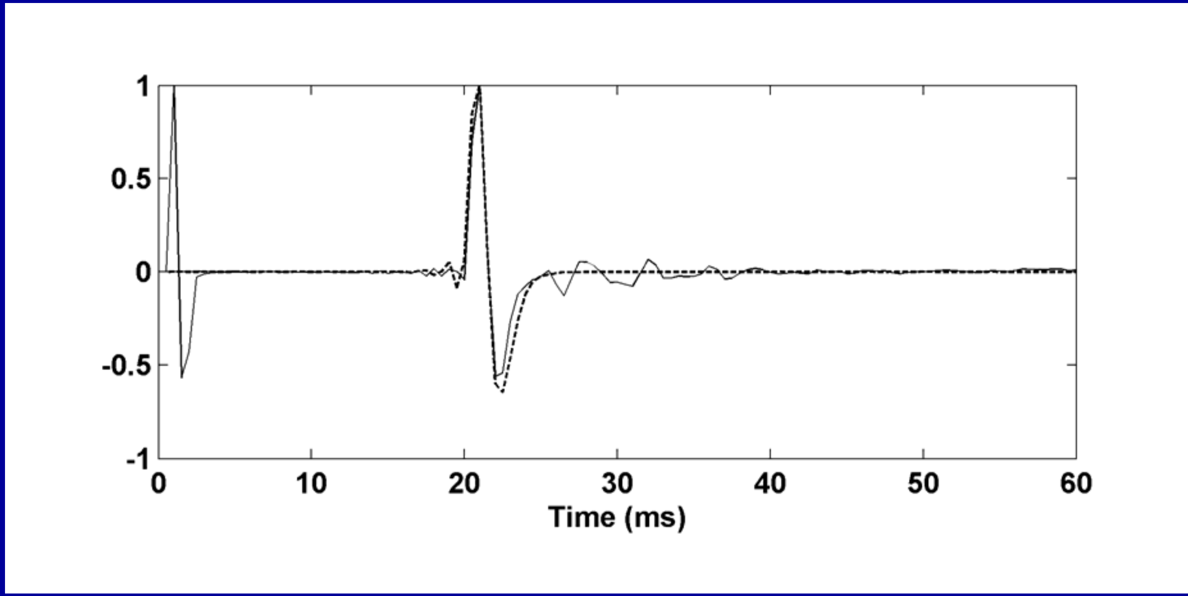
- The Problem
- Background
- Theory
  - Approach
  - Results
- **Data**
  - Field measurement
  - Results
- Conclusion

Field measurements on Sand



We made acoustic pulse measurements with blank pistol shots as the source. We also directly measured soil density and permeability.

Field measurements on Sand

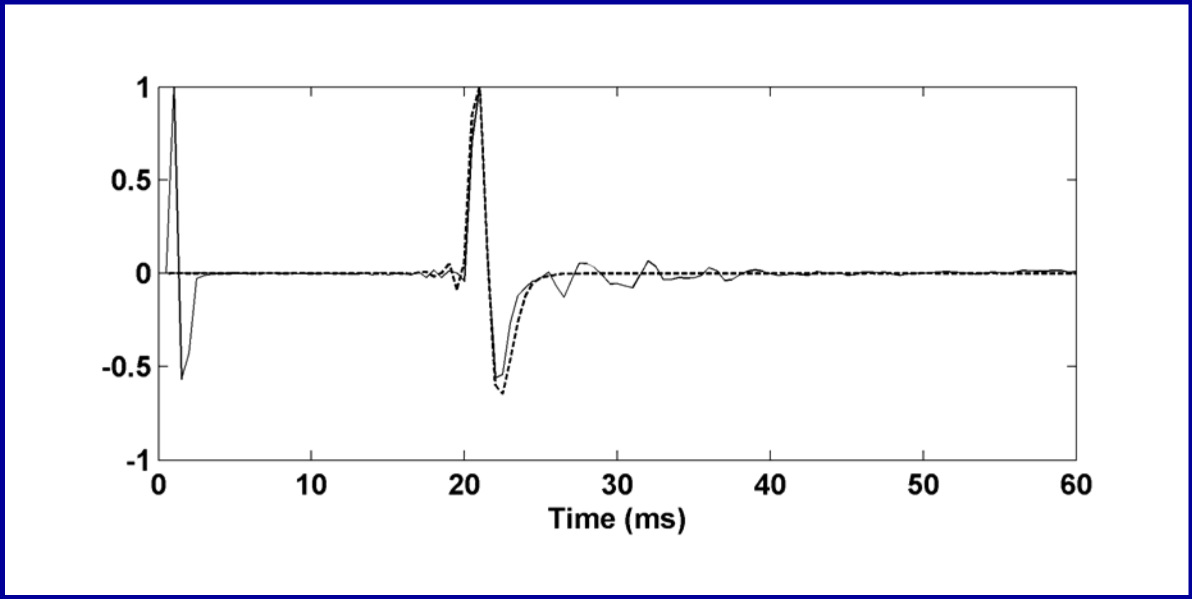


- We use the source pulse of the pistol (previously measured, and corrected for nonlinear effects) to calculate the theoretical acoustic pulse shape.

- The soil properties are (automatically) varied until the theoretical waveform matches the measured waveform.

- This allows us to determine the soil permeability.

Field measurements on Sand



From the measured acoustic waveforms and sand density:

- Depth of penetration determined to be 10 cm.
- Acoustically-determined permeability was 0.9×10^{-10} m^2.
- The measured sample permeability was 0.6×10^{-10} m^2.

Conclusions

- We have discovered that surface acoustic pressure waves can penetrate to sufficient depths in soil to be of interest in a variety of applications.

- Theoretical results show depths of penetration ranging from 1 to 100 cm for common materials like sand and gravel.

- A field trial on sand at the Desert of Maine yield a depth of penetration of 10 cm, and yield an acoustically-predicted permeability close to the measured permeability.

- Further research will investigate the scaling features that link cm-scale direct measurements to the meter-scale non-invasive measurements.